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Dynamical-friction galaxy–gas coupling and cluster cooling flows

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ABSTRACT

We revisit the notion that galaxy motions can efficiently heat intergalactic gas in the central regions of clusters through dynamical friction. For plausible values of the galaxy mass-to-light ratio, the heating rate is comparable with the cooling rate due to X-ray emission. Heating occurs only for supersonic galaxy motions, so the mechanism is self-regulating: it becomes efficient only when the gas sound speed is smaller than the galaxy velocity dispersion. We illustrate with the Perseus cluster, assuming a stellar mass-to-light ratio for galaxies in the very central region with the dark matter contribution becoming comparable with this at some radius r_{s}. For $r_{\mathrm{s}} \lesssim 400$ kpc $\sim 3r_{\mathrm{cool}}$ – corresponding to an average mass-to-light ratio of $\sim$10 inside that radius – the dynamical-friction coupling is strong enough to provide the required rate of gas heating. Such values of r_{s} are associated with total mass attached to galaxies that is about 10 per cent of the mass of the cluster – consistent with values inferred from numerical simulations and observations. The measured sound speed is smaller than the galaxy velocity dispersion, as required by this mechanism. With this smaller gas temperature and the observed distribution of galaxies and gas, the energy reservoir in galactic motions is sufficient to sustain the required heating rate for the lifetime of the cluster. The galaxies also lose a smaller amount of energy through dynamical friction to the dark matter implying that non-cooling-flow clusters should have flat-cored dark matter density distributions.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: formation – galaxies: interactions – galaxies: kinematics and dynamics.

1 INTRODUCTION

Galaxy cluster gas loses thermal energy copiously through X-ray emission. In the absence of energy input, radiative cooling in cores of clusters should result in substantial gas inflow (see Fabian 1994, for a review). These 'cooling flows' would have associated mass-deposition rates of several hundred $\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ in some clusters (Peres et al. 1998). Nevertheless, recent high-resolution X-ray observations (e.g. Peterson et al. 2001, 2003) have revealed that there is little evidence for the expected multi-phase gaseous structures, strongly suggesting that mass dropout is being prevented by some source that is heating the gas, thereby balancing radiative energy loss in the central region of clusters. Recent work has focused on two prospective heating mechanisms: (1) diffusive heat transport, via thermal conduction (Tucker & Rosner 1983; Bregman & David 1988; Narayan & Medvedev 2001; Fabian, Voigt & Morris 2002; Ruszkowski & Begelman 2002; Voigt et al. 2002; Kim & Narayan 2003a; Zakamska & Narayan 2003) and/or turbulent mixing (Cho et al. 2003; Kim & Narayan 2003b; Voigt & Fabian 2004), from hotter gas in the outer region to that in the core; (2) energy input from jets, outflows and radiation from a central active galactic nucleus (Ciotti & Ostriker 2001; Brüggen & Kaiser 2002; Churazov et al. 2002; Kaiser & Binney 2003).

There is, however, at least one additional mechanism that appears to have been overlooked. It involves the energy lost by concentrated clumps of matter (galaxies) as they move through the cluster. Part of this energy may go into re-arranging the dark matter mass distribution (El-Zant et al. 2004), but a significant fraction should end up deposited in the gas. That dynamical-friction (DF) coupling can transform the dynamical energy of galaxies into thermal motion in the gas has been known for at least four decades (e.g. Dokuchaev 1964). Relatively recent work involving this notion includes the analysis by Miller (1986) of the Perseus cluster and that of Just et al. (1990) concerning the Coma cluster. Both studies confirm that, provided the mass-to-light ratio of galaxies is $\sim$20, the energy lost by galaxies to the gas should be sufficient to counteract the radiative cooling of the gas in the central region of these clusters.

Several developments on the empirical side suggest renewed relevancy for this mechanism. One obvious one involves recent X-ray data confirming that a heating mechanism *is* required. Whereas the consensus in the 1980s was against this conclusion, it now seems

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inescapable. The second involves revisions to the inferred gas electron densities in the central region of clusters; best values referred to by Miller and Just et al. are of the order of 10^{-3} cm^{-3}, while current best estimates are rather in the range 10^{-2}–10^{-1} cm^{-3} (Kaastra et al. 2004). This leads to an order-of-magnitude increase in the dynamical friction coupling between the galaxies and gas. There has also been progress in determining the mass-to-light ratio of galaxies. On the theoretical side, work by Just et al. (1990) and Ostriker (1999) has since shed some light on the behaviour of the dynamical-friction coupling in a gaseous medium in the transonic and subsonic regimes.

There appears to be a priori no reason why the rate of energy loss from galaxies to gas via dynamical friction should be of the same order as that radiated by the gas. However, *this coupling is active only when the sound speed of the gas is smaller than the typical velocity of galaxies*. The mechanism is therefore self-regulating; the gas cools until the dynamical-friction heating rate is always equal to the cooling rate. This possibility, already alluded to by Miller (1986), is especially relevant in connection with the observed temperature drop in the central, cooling, regions of clusters. Although this, in itself, does not guarantee that the process is stable, the self-regulating character suggests the gas temperature in the central region could change with radius in such a way as to match the radial dependence of the radiative cooling.

We start by pointing out, in the next section, why this is expected to be so, before moving on to develop a Monte Carlo model to estimate the total energy expected to flow into the cooling region of the Perseus cluster, using recent data for galaxy luminosities and projected positions, as well as for the gas parameters of that cluster, and averaging over a set of different realizations where three-dimensional positions, velocities and mass-to-light ratios are treated as stochastic quantities. The final Section discusses briefly the central dark matter distribution and energetics, as well as some remaining questions.

2 DYNAMICAL FRICTION IN GASEOUS SYSTEMS

The fundamental difference between the dynamics of collisionless and gaseous systems is the existence in the latter case of pressure gradients which communicate forces at the sound speed c_s. If the galaxy velocity V is much larger than c_s then the gravitational interaction between a particle at impact parameter b leading to dynamical friction is unaffected by pressure forces (because by the time these are communicated to that region the galaxy is already at a distance $b\sqrt{1+(V/c_s)^2} \gg b$; see, for example, Ruderman & Spiegel 1971). If, on the other hand, $V < c_s$, pressure forces can be communicated to the perturbed region *before* the minimum distance b is achieved. The resulting pressure gradients ensure that the displacement of gas particles therein is hindered, and so the cumulative back reaction on the perturber that results in the dynamical-friction force is drastically reduced.

In the collisionless case, when one speaks of a particle one has in mind an actual material constituent. In the classic Chandrasekhar formulation, each of these contributes individually. The sum of the perturbations from particles moving faster than the perturber (a galaxy) is negligible for small particle mass (being proportional to that mass). That from slower particles, however, results in a net contribution that for the massive perturber is independent of the smaller background-particle mass, and is always directed opposite to the perturber's motion. This results in the gradual decrease in the dynamical-friction force when the perturber velocity falls below that of the typical background particle. In the gaseous case, however, unless the mean free path is larger than the impact parameter, collisions will lead to rapid decoherence of individual particle motion. A coherent effect that results in dynamical friction should then involve interactions between the perturber and gaseous elements instead of individual particles. If the bulk velocity, i.e. the macroscopic motion, of the gas elements is smaller than that of the perturber then all gas elements will contribute.

The above considerations suggest that gaseous dynamical friction will follow the high-velocity approximation in a collisionless medium when $V > c_s$ and then drop sharply when $V < c_s$. This conclusion had already been reached on the basis of steady-state perturbation theory (Ruderman & Spiegel 1971; Raphaeli & Salpeter 1980) and was confirmed by two more sophisticated, but rather different, techniques invoking time dependence (Ostriker 1999) and fluctuation theory (Just et al. 1990). Simulations by Sanchez-Salcedo & Brandenburg (1999) have shown broad agreement for particles moving on rectilinear trajectories and, more importantly, qualitatively confirmed the above conclusions in spherical systems (Sanchez-Salcedo & Brandenburg 2001). For a perturber of mass M_p, moving with $V > c_s$ we will thus assume that energy is lost at a rate given by

$$\frac{dE}{dt} = \frac{4\pi(GM_p)^2\rho_g}{V} \ln \frac{b_{max}}{b_{min}}, \tag{1}$$

and that the energy loss vanishes for $V < c_s$.

The relevant density ρ_g is the typical gas density to be found within the cluster cooling radius r_{cool}, inside which the cooling time is less than a Hubble time – i.e. the region where heating must be invoked. If the galaxy is inside this radius, the range of impact parameters that contribute to heating should, to a first approximation, correspond to a minimal scale determined by the galaxy size and a maximal one determined by the cooling radius. For these galaxies, therefore, we take the Coulomb logarithm to be $\ln(r_{cool}/r_0)$, where the 'galaxy radius' r_0 is set to 10 kpc – about twice the effective radius and disc scale-length for ellipticals and spirals, respectively. Galaxies outside r_{cool} should also contribute, but in this case the contribution from material inside r_{cool} to the energy lost by a galaxy at radius r [1] comes from impact parameters between $\max(r_0, r - r_{cool})$ and $r + r_{cool}$. This contribution is also restricted from within an angle $2\tan^{-1}[r_{cool}/(r - r_{cool})]$. This is a one-dimensional angle because the remaining dimensions are accounted for by the integration over impact parameters.[2]

[1] We measure galaxy radii relative to the position of the CD galaxy, which is also taken to be the position of the centre of the cooling region.

[2] It is customary, for particles moving inside a matter distribution, to ignore boundary effects, integrating over constant maximum impact parameters and all angles (cf. equations 7–11, 7–12 of Binney & Tremaine 1987, hereinafter BT). This is what is assumed here for galaxies inside r_{cool}. Also, strictly speaking, for $r \gg r_{cool}$, $\ln \Lambda$ should be replaced by $\frac{1}{2}\ln(1+\Lambda^2)$ (since $\Lambda \sim 1$, cf. BT, p. 423). This correction, leading to an increase of ~15 per cent in the total DF power, is also not accounted for here. Nevertheless, it is essential to include an angular correction when $r > r_{cool}$, as the angle subtended by r_{cool} rapidly decreases. We limit ourselves here to the introduction of a multiplying factor, instead of an angle dependent b. Other possible forms for this factor include $\tan^{-1} r_{cool}/\sqrt{r^2 - r_{cool}^2}$, the angle subtended by a spherical region with sharp boundary at r_{cool}. For the form we chose, however, the average value of $\ln(b_{max}/b_{min})$ within the immediate vicinity of the cooling region ($\sim 1.5 r_{cool}$) is closer to that inside, thus the discontinuity at the edge is reduced. At larger radii, the two forms converge.

Replacing the minimal impact parameter with $r - r_{\rm cool}$ leads to an error of $\lesssim$1 per cent in the results. For galaxies outside $r_{\rm cool}$, therefore,

$$\ln\left(b_{\max}/b_{\min}\right) \rightarrow \frac{1}{\pi}\tan^{-1}\frac{r_{\rm cool}}{r - r_{\rm cool}} \ln\frac{r + r_{\rm cool}}{r - r_{\rm cool}}. \quad (2)$$

For galaxies on highly eccentric trajectories, the bulk of the energy exchange with gas inside the cooling radius takes place at closest approach to $r_{\rm cool}$. However, corrections due to this effect are not large, even if most galaxies are indeed on nearly radial orbits. For any individual realization of such a highly anisotropic quasi-steady-state system, the dominant contribution to the energy input will come from those galaxies that are at small radii (since both terms on the right-hand side of equation 2 rapidly decrease when r is appreciably larger than $r_{\rm cool}$) and are thus on their closest approach.

3 THE PERSEUS CLUSTER

Because of the rather large energy input rate ($\sim10^{45}$ erg s^{-1}) that is required to prevent a cooling flow, the Perseus cluster is one of the more demanding cases for any cluster-heating model. In this section we examine whether, even in this case, energy dissipated from cluster galaxies can be sufficient to provide the required power.

Brunzendorf & Meusinger (1999) have collected a catalogue of projected positions and apparent B-band luminosities of 660 galaxies in the Perseus cluster. In Fig. 1 we plot the cumulative number of galaxies as a function of projected radius R. As Fig. 1 shows, this can be fitted over a large range in radius by a distribution $N(R) \sim R$, which implies a projected density distribution $n(R) \sim 1/R$. This in turn implies a three-dimensional density varying as $\sim1/r^2$. In this case, along the line of sight, and at any given R, the number density of galaxies decreases as $\sim(R^2 + Z^2)^{-1}$ (with $r^2 = R^2 + Z^2$). This simple dependence of the number-density distribution on Z is consistent with the latter being distributed in such a way that $|Z| = R \tan X$, with X being a random variable uniformly distributed between 0 and $\pi/2$. This is how the third spatial coordinate is chosen in the random realizations of the Perseus cluster that we describe below. Since the density does drop more sharply than $1/r^2$ at large radii, this prescription will slightly overestimate the Z-values of coordinates. This is, however, a minor effect – since that region does not contain many galaxies and since most of the DF comes from inner cluster galaxies (and, if anything, leads to a decrease in the total DF power pumped into $r_{\rm cool}$).

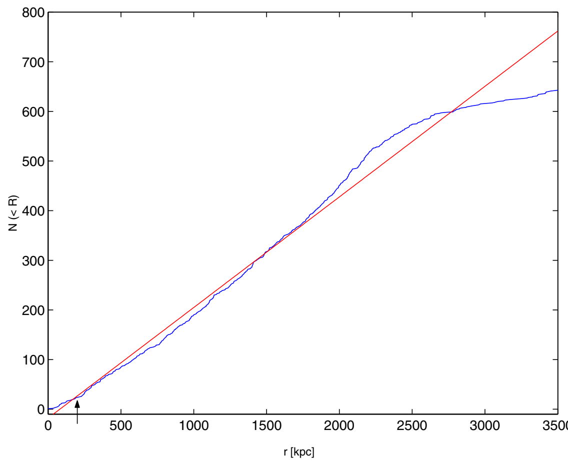

Figure 1. Number of galaxies inside projected radius R that can be approximated by a linear fit (top) over a large range in radii and with limited relative error (bottom). The arrow indicates the cooling radius.

Galactic extinction is particularly severe at the position of the Perseus cluster in the sky. Trials with the NED calculator show that corrections in the central region vary between ~ -0.65 and ~ -0.9, with a value of about -0.7 mag at the CD galaxy NGC 1275 (which is not included in the DF calculations). To all galaxies in the catalogue we will apply an extinction correction of -0.75 mag. To this one needs to add a K-correction that ranges from -0.092 for ellipticals to -0.02 for late-type spirals. The apparent magnitude of discs are, however, further affected by inclination effects. These vary as $A_i \approx -\log(a/b)$, with $b/a \approx \cos i$ (assuming the axis ratio of the galaxy viewed edge on to be vanishingly small). This gives an average correction $A_i = -0.19$. We also apply a cosmological dimming correction of $10\log(1+z) = -0.085$ to all galaxies. Absolute magnitudes are then obtained by assuming a distance to the Perseus cluster of 78 Mpc, compatible with a Hubble parameter $H_0 = 100\,h$ km s^{-1}Mpc^{-1} with $h = 0.7$ and redshift $z = 0.0183$ assumed by Brunzendorf & Meusinger (1999). We also adopt their prescription for transforming angular into projected distances (1 arcmin = 31.5 h_{50}^{-1} kpc).

Unless the structural parameters defining the density distribution of elliptical galaxies vary significantly with mass, the Faber–Jackson relation and the virial theorem imply a luminosity-dependent central mass-to-light ratio: $M/L \sim L^{\gamma}$, with $\gamma \sim 0.3$–0.4. Gerhard et al. (2001) have dynamically examined the central mass-to-light ratio of a sample of elliptical galaxies and determined that their results are in agreement with the assumption of structural homology, and that the variation of the mass-to-light ratio within an (elliptical galaxy's) effective radius is largely due to change in stellar population. Although Trujillo, Burkert & Bell (2004) have argued that non-homology effects may be important in determining γ (which they deduce to be $\sim$0.1), a stellar mass-to-light variation with $\gamma \sim 0.4$ also appears to exist for disc galaxies (Salucci, Ashman & Persic 1991). All these relations exhibit significant scatter. We adopt a zero-point mass-to-light ratio (which we will refer to as 'stellar', even though the aforementioned papers do not exclude a modest dark matter contribution in the inner regions) consistent with these results and containing a stochastic component to represent the scatter. Thus for a galaxy of luminosity L we adopt

$$\left(\frac{M}{L}\right)_S = 10 \times X \left(\frac{L}{5\times10^{10}\,{\rm L}_\odot}\right)^{0.3}, \quad (3)$$

where X is a random variable chosen from a normal distribution with an average of unity and a dispersion 0.7. (The normalization is chosen by inspection of fig. 13 of Gerhard et al. 2001.)

The average mass-to-light ratio inside a given galaxy radius is expected to increase as that radius becomes larger – as the dark matter contribution becomes progressively more important (e.g. Takamiya & Sofue 2000; Gerhard et al. 2001). For galaxies confined in clusters, the contribution of dark matter to the mass-to-light ratio will depend on how much of the halo that should be surrounding the galaxy has been removed, i.e. on the radial extent of the part of the galaxy halo that has survived stripping due to interaction with the cluster halo, and so has remained attached to the galaxy instead of becoming part of the cluster halo. This will in turn depend on the maximum excursion of that galaxy into the cluster centre, and the density distributions of both the galaxy and the cluster.

The radius to which material is stripped is normally defined in terms of the Roche limit: $r_{\rm t} = [m(r_{\rm t})/M(r)]^{1/3} r$. The tidal radius $r_{\rm t}$ is thus defined implicitly in terms of the separation r between the two systems. In some cases, nevertheless, it is possible to obtain

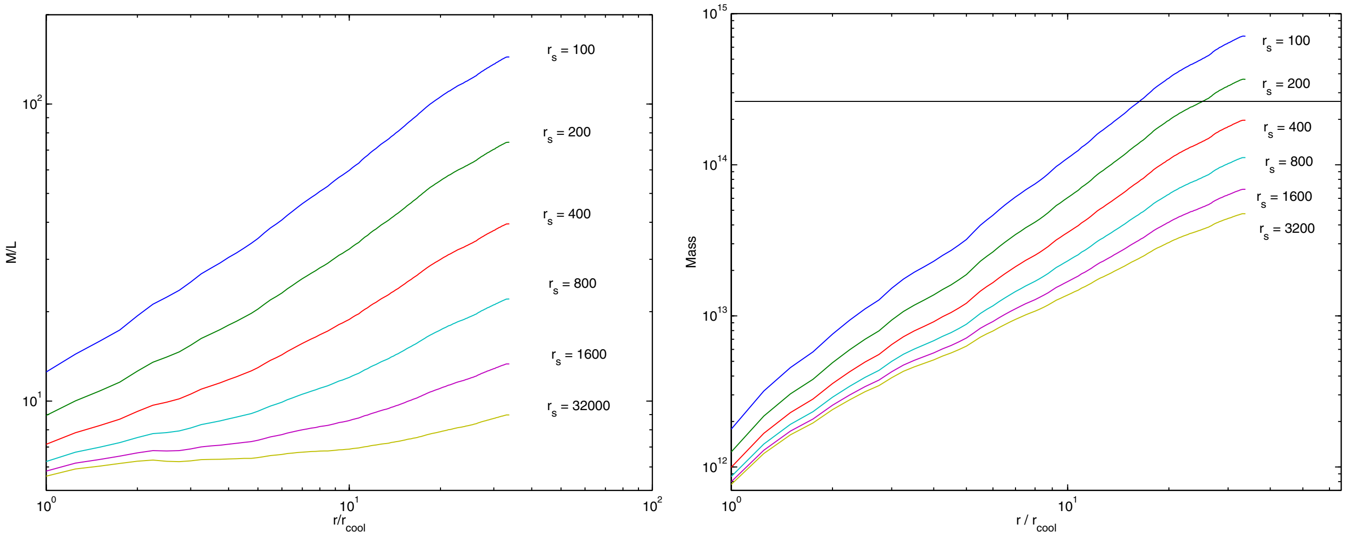

Figure 2. Mass-to-light ratios for galaxies inside radius r deduced from equation (4) over 10 000 random realizations of the Perseus cluster data (left) and the total mass in galaxies thus inferred. The curves are labelled according to the values of the parameter r_s, which is given in kpc. The mass on the right-hand panel is in units of $M_\odot$ and the horizontal line therein refers to about 10 per cent of the total cluster mass at the maximum radius shown (assuming isotropic three-dimensional velocity dispersion of 2000 km s^{-1}). All labels pertaining to values of r_s again assume length units of kpc.

explicit expressions. For example, in the case of a singular isothermal sphere with characteristic velocity dispersion $\sigma, M(r) = (2\,\sigma^2/G)\,r$. Therefore, that sphere, when moving through another isothermal system with dispersion $\Sigma > \sigma$, will be cut to a radius $r_t = (\sigma/\Sigma)\,r_{\min}$, if $r_{\min}$ is the minimum distance that the centres of the two spheres achieve. And so, in this approximation of the situation, an average galaxy halo (velocity dispersion ~200 km s^{-1}) moving through the Perseus cluster (velocity dispersion ~2000 km s^{-1}), will have $r_t \sim r_{\min}/10$ and the mass enclosed within this radius will be $(2\sigma^2/G)r_t$. Since haloes found in cosmological simulations have density profiles that are close to singular isothermal spheres over a large range in radii, this representation should be sufficient in approximating the initial conditions before any modification of these profiles takes place – provided that the density of the galactic haloes is scaled in such a way that the mass in the very inner region is not dominated by the dark matter, so as to be in line with the aforementioned studies concerning the central mass-to-light ratios of galaxies.

In line with these considerations, namely that the mass in galaxy haloes $\propto r_t$ and $r_t \propto r_{\min}$, we will assume that the radial variation of the mass-to-light ratio of cluster galaxies is given in terms of their position in the cluster by

$$\frac{M}{L} = \left(1 + Y\frac{r}{r_s}\right)\left(\frac{M}{L}\right)_S, \qquad (4)$$

where $(M/L)_S$ is defined by equation (3) and $r_s = GM_{\rm lum}/\sigma^2 \sim f(r/10)$ (with $f = r_{\min}/r$ and $M_{\rm lum}$ the luminous mass) defining a spatial scale over which enough dark matter remains tied to the galaxy for its contribution to the total mass to be comparable with the luminous one. Statistically, f will be determined by the velocity distribution of galaxies, with more anisotropic dispersions implying deeper entries into the cluster core and so more stripping. Uncertainty in this parameter is represented by an additional appeal to another random variable Y, again chosen from a normal distribution with mean unity and dispersion 0.7. In Fig. 2 we show the average mass-to-light ratio within a given radius for the Perseus cluster averaged over 10 000 realizations of the random variables X and Y. Also shown is the radial variation cumulative mass in galaxies for different values of r_s. The horizontal line refers to 10 per cent of the total mass of the cluster at the maximum radius shown. This is the mass fraction that is expected to be attached to galaxies both theoretically (Ghigna et al. 2000) and observationally (Natarayan, Kneib & Smail 2002).

Another dynamical variable determining gas–galaxies DF coupling is the velocity distribution of the latter. Brunzendorf & Meusinger have only determined the line-of-sight speeds of 169 of the galaxies in their samples. The velocity dispersions of galaxies, when binned radially in groups of 20 to 30, are ~1000–1400 km s^{-1} with no obvious systematic variation incompatible with small-sample statistics. Fig. 2 shows the energy expected to be deposited via dynamical friction into $r_{\rm cool}$, from galaxies enclosed within a radius r, relative to the energy radiated from the cooling region, for different values of the radial scale r_s. For each velocity component a normal distribution with zero mean and dispersion σ, such that $\sqrt{3}\sigma = 2000\,{\rm km\,s^{-1}}$, is assumed. Results are shown for the 10 000 realizations of the cluster in Fig. 3, assuming $r_{\rm cool} = 130$ kpc, and the total energy emitted from $r < r_{\rm cool}$ to be 5×10^{44} erg s^{-1}, consistent with the findings of Kaastra et al. (2004), when converted to correspond to $h = 0.7$. [3]

It is apparent from Fig. 3 that for the DF to provide the bulk of the energy that can balance radiative energy loss one needs $r_s \lesssim 400$ kpc. This is consistent with what is independently found from Fig. 2,

[3] In Kaastra et al., table 11 lists the cooling radius of the Perseus cluster as 177 kpc at 15 Gyr. The geometric factor $0.5/h$ reduces this to 126.4 kpc. But the cooling time decreases as $h^{-1/2} = 1/1.183$ (because of its dependence on the electron density), which would increase the cooling radius by a factor of $h^{0.5\times0.67} = (0.7/0.5)^{0.335} = 1.12$. This gives a cooling radius of 141.6 kpc at 15 Gyr. Scaling back to our adopted value of $r_{\rm cool} = 130$ kpc implies that the cooling time decreases by a factor of $(141.6/130)^{1/0.67}$, to 13.2 Gyr. Close to the value derived from the WMAP results. It is also close to the value obtained by simple geometric transformation, which means that the total luminosity within $r_{\rm cool}$ is similar to the value given in table 12 of Kaastra et al., multiplied by the distance factor $(0.5/h)^2$.

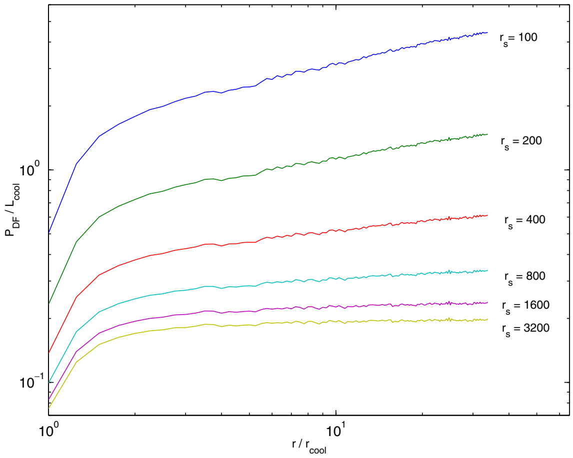

Figure 3. Power expected (over ten thousand random realizations of the cluster) to be transmitted to gas inside $r_{\rm cool}$ via dynamical friction on cluster galaxies within radius r, relative to the total power radiated from within $r_{\rm cool}$.

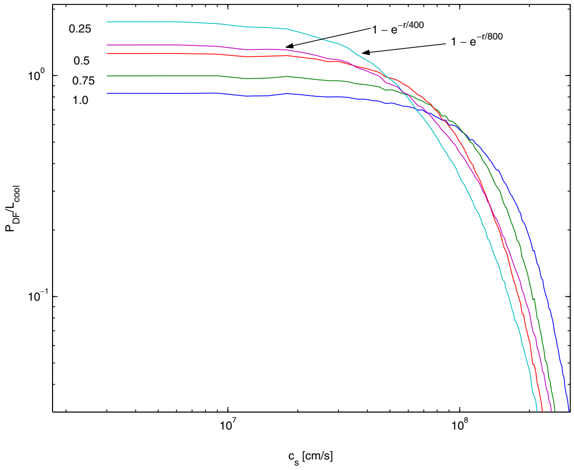

Figure 4. Same ordinate as in Fig. 3 but plotted against the gas sound speed for different (constant as well as radially varying) values of the ratio of the velocity dispersions σ_θ/σ_r (and assuming $\sigma_\phi = \sigma_\theta$). In these plots $r_s =$ 400 kpc and $r/r_{\rm cool}$ is set to 35 (about the same as the maximum value shown in Fig. 3).

namely that a value of 200 kpc $\lesssim r_s \lesssim$ 400 kpc produces the correct cluster mass fraction attached to galaxies (∼10 per cent, according to the simulations of Ghigna et al. 2000 and the observations of Natarayan et al. 2002).

The sound speed, which can be written in terms of the mean molecular weight (which we assume to be $\mu = 0.62$) as $c_s = \sqrt{\gamma RT/\mu}$, can also be read off table 5 of Kaastra et al. (2004). Excluding the very inner data point, which is probably influenced by central activity (Churazov et al. 2003), the central sound speed starts at about 880 km s^{-1}, eventually rising with radius to reach an asymptotic limit about one and a half times that value, but remaining largely constant within most of the cooling region (Churazov et al., fig. 8). These studies also show the electron density to be slowly varying within $r_{\rm cool}$, with values in the range 0.1 −0.005 cm^{-3} (there is also a factor of $\sqrt{0.7/0.5}$ that should be included because we use $h = 0.7$, as opposed to the value $h = 0.5$ used by these authors). In calculations shown in Fig. 3, a value of 0.02 cm^{-3} is used. This is converted into gas density using $\rho_g = \mu_e m_p n_e$, with the mean molecular weight per electron $\mu_e = 1.18$ and m_p the proton mass. The value of the sound speed is set to $c_s = 900$ km s^{-1}.

Because of the sharp cut-off in the DF-mediated coupling when $V < c_s$, the amount of energy deposited into the gas must sensitively depend on the relative magnitude of the galaxy velocities and the sound speed when $V \sim c_s$. The former is a function of the anisotropy of the distribution. For example, if galaxies move on nearly radial trajectories, their velocity dispersion would be closer to the line-of-sight value of 1200 km s^{-1}, rather than 2000 km s^{-1} as assumed above. The simulations of Ghigna et al. (2000) suggest that galaxies (as represented by cluster subhaloes) may have biased velocity dispersion in the central region, perhaps reflecting enhanced radial motion; whereas at larger radii they have velocity distributions that rather closely follow that of the dark matter. Fig. 4 shows the power pumped into the gas relative to that radiated within the cooling radius of the Perseus cluster, as predicted by our model, as a function of the sound speed for a range of fixed and (radially) varying σ_θ/σ_r values (assuming $\sigma_\phi = \sigma_\theta$) for $r_s = 400$ kpc. It is rather remarkable that the competing effects of increased coupling at low velocities (because of the $1/V$ dependence), and the rapidly decreasing number of galaxies contributing to the DF with increasing c_s, conspire to ensure that the sharp drop in the energy input rate is always attained only when $c_s \gtrsim 900$ km s^{-1}, precisely the value in the (central) region where the temperature drops in the cluster. Similar behaviour is found for other values of r_s, though the normalization of the curves is different (as can be expected from Fig. 3).

4 CONCLUDING REMARKS

That dynamical-friction coupling between cluster galaxies and gas can significantly heat the latter component is not a new concept. Indeed Miller (1986) has pointed out that a few luminous galaxies in the Perseus cluster's central region may alone deposit sufficient energy to keep gas in that region from cooling, provided that they had a mass-to-light ratio of about 20. We revisited this cluster using recently compiled galaxy and gas data and determinations of the mass-to-light ratios in galaxies. Our Monte Carlo model shows that the rate at which energy is deposited by galaxies into the gas within the cooling radius can completely compensate for radiative loss from within that radius, if galaxies at radii $\lesssim$400 kpc from the centre of the cluster have dark mass comparable with their stellar mass (with galaxies at smaller radii having progressively smaller dark matter content, vanishing for those near the centre of the cluster). The associated average mass-to-light ratio within this radius is about 10, and the total mass attached to the galaxies is about 10 per cent the mass of the cluster, which is consistent with both simulations and observations of galaxy clusters.

A robust and potentially important prediction of the model is that the drop in gas temperature invariably observed in the cooling regions of clusters is necessary for the DF coupling to be sufficiently strong. There is a natural interpretation for this phenomenon: the gas cools until dynamical-friction heating becomes sufficiently efficient to prevent a further drop in temperature. The gas random motion is then coupled to that of the galaxies, and so remains in approximate equilibrium with it. All this simply follows from the fact that dynamical friction drops sharply for subsonic motion. In the case of the Perseus cluster, the transition from weak to strong coupling occurs precisely in the range of sound speeds found in the cooling core of the cluster, as can be seen from Fig. 4 (note that in this plot we do not take into account the expected increase in gas density as it cools, which further increases the coupling of the colder component following a temperature drop. We expect to discuss this and related issues in detail in a forthcoming paper.)

The action of the mechanism discussed in this paper also has consequences for the dark matter distribution. As shown by El-Zant et al. (2004), dynamical friction from the galaxies will heat a density cusp, creating a core with radius corresponding to roughly a fifth of the original Navarro, Frenk & White (1997) scale-length (cf. fig. 1 of El-Zant et al.), where dark matter has been spread out to larger radii (fig. 3 of El-Zant et al.). Approximating the initial density distribution in this region such that $\rho_i = \rho_0\ (r_0/r)$ and the final one with $\rho_f = \rho_0$, the energy required for this transformation is $\Delta\Phi = (8\pi G)^{-1}\int_0^{r_0}(|\mathrm{d}\phi/\mathrm{d}r|_i^2 - |\mathrm{d}\phi/\mathrm{d}r|_f^2)4\pi r^2\,\mathrm{d}r = 22\pi^2 G\rho_0^2 r_0^5/45$ [with $\mathrm{d}\phi/\mathrm{d}r = (4\pi G/r^2)\int \rho r^2\,\mathrm{d}r$].

Taking $r_0 = r_{\rm cool}$, and assuming the ratios of the gas-to-dark matter densities at that radius to be similar to the ratio of gas-to-dark matter mass inside it, one can convert the observed electron density into the expected dark matter density, after modification by dynamical friction. For example, using equation (4) of Churazov et al. (2003) for the electron density, after rescaling the radial scales with a factor $0.5/0.7$ and the numerical multipliers by a factor $(0.7/0.5)^{1/2}$, in order to transform from $h = 0.5$ used by these authors to $h = 0.7$ adopted here, the electron density is $n_{\rm e}(r_0) = 0.0053\ \mathrm{cm}^{-3}$. The gas density is then $\rho_{\rm g} = \mu_{\rm e} m_{\rm p} n_{\rm e}$ (where, as before, $\mu_{\rm e} = 1.18$ and $m_{\rm p}$ is the proton mass). Taking ρ_0 to correspond to about nine times this, one finds $\Delta\Phi = -3 \times 10^{61}$ erg, which is comparable with the binding energy of the cD galaxy $\Phi_{\rm cD} \approx -(GM_{\rm cD}^2/R_{\rm cD}) = 1.4 \times 10^{61}$ erg$(M_{\rm cD}/\ 2 \times 10^{12}\ \mathrm{M}_\odot)$ (25 kpc$/R_{\rm cD}$) (in the context of the model outlined in Section 3 the cD galaxy has luminosity $1.4 \times 10^{11}\ \mathrm{L}_\odot$ and the stellar mass-to-light ratio is, for equation (3) with $X = 1$, 13.6. The above estimate assumes there is no dark matter attached to it). The energy from gas inside the cooling radius for the age of the cluster is somewhat larger (e.g. for five Gyr this amounts to 8×10^{61} erg). Nevertheless, this energy is easily available from fast-moving galaxies from beyond the very inner region – for example its value coincides with the kinetic energy in a mass similar to that of the CD galaxy and moving at 2000 km s^{-1}, and that material can be supplied solely by the stellar mass of galaxies within $2r_{\rm cool}$ – the region from which, according to our model, the bulk of energy input to the gas comes.

It is worth noting here that, under the circumstances just described, the mass of the gas within $r_{\rm cool}$ (which, using equation 4 of Churazov et al. 2003, adjusted for $h = 0.7$ with $r_{\rm cool} = 130$ kpc, amounts to $2.6 \times 10^{12}\ \mathrm{M}_\odot$) is comparable with that of the galaxies in that region (cf. Fig. 2). Owing to the temperature drop in the gas, thermal motions can be significantly smaller than that of the galaxies. The energy of the gas can therefore be smaller than that of the galaxies by a factor of a few. There is therefore sufficient energy in galaxies to heat the gas several times over, especially as galaxies at all radii contribute – with the crucial parameter, which was the focus of this paper, being the rate at which this is transferred. Furthermore, once the dark matter in the centre has been heated, it absorbs little additional energy from the galaxies, since dynamical friction does not act on fast particles, and the coupling with the dark matter at larger radii decreases rapidly with radius (see El-Zant et al. 2004 for further discussion). The energy lost to the dark matter is therefore less than that going into keeping the gas at constant temperature. The mass of the CD galaxy, as well as the spatial and velocity distribution of galaxies in the central region of the cluster, will reflect the history of energy loss to both components. The data used for this paper does indeed show significant mass segregation in the galaxy distribution.

Several questions remain open. Prominent among these is the issue of thermal stability. From their conclusion that thermal stability requires a remarkably narrow range of heating rates, Bregman & David (1989) have argued against Miller's proposition that the Perseus cluster gas is heated by DF from galaxies. However, the functional form of the heating rate used by these authors does not agree with later calculations that have been borne out by numerical studies – e.g. their postulated form has a *negative* energy transfer rate ($\sim -1/V^3$) for highly subsonic velocities, resulting in gas *cooling*, which is incompatible with the positive (even if small) heating found by Just et al. (1990) and Ostriker (1999) in that limit. Even though there seems to be some situations where such 'cooling wakes' can materialize (Fabian et al. 2001; Bayer-Kim et al. 2002; David et al. 1994). It will be interesting to see how generic they are. To answer this question, it will be necessary to perform simulations of the interaction process between galaxies and gas in realistic background gravitational potentials, or by including self-consistently the full self-consistent gravitational potential of the material constituting the cluster.

These calculations would also address another crucial question, that concerning the precise manner in which the energy lost by the galaxies is distributed in the gas. We have adopted the simple approach where this energy is deposited isotropically and equally in logarithmic intervals. This should approximate how the energy is initially deposited, at least for highly supersonic galaxies (and since, in the cooling region, the sound speed may be several times smaller than the velocity dispersion, this may not be a very bad assumption). Even then, however, the deposited energy may still be transported toward the centre of the cluster by wave motions, as suggested, for example, by Balbus & Soker (1990), and redistributed. We note here that the claim of these authors that DF from galaxies is insufficient to heat the cluster core is based upon outdated values for the electron density and an outdated $(1/r)$ gas distribution. With updated values for the electron density and gas distribution (e.g. the empirical formula of Churazov et al. 2003), their conclusions are changed, as we have shown. We thus conclude that it is far from obvious that DF heating of cluster gas is irrelevant.

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REFERENCES

Balbus S. A., Soker N., 1990, ApJ, 357, 353
Bayer-Kim C. M., Crawford C. S., Allen S. W., Edge A. C., Fabian A. C., 2002, MNRAS, 337, 938
Binney J., Tremaine S., 1987, Galactic Dynamics. Princeton Univ. Press, Princeton (BT)
Bregman J. N., David L. P., 1988, ApJ, 326, 639
Bregman J. E., David L. P., 1989, ApJ, 341, 49
Brüggen M., Kaiser C. R., 2002, Nat, 418, 301
Brunzendorf J., Meusinger H., 1999, A&AS, 139, 141
Cho J., Lazarian A., Honein A., Knaepen B., Kassinos S., Moin S., 2003, ApJ, 589, L77

Churazov E., Sunyaev R., Forman W., Böhringer H., 2002, MNRAS, 332, 729
Churazov E., Forman W., Jones C., Böhringer H., 2003, ApJ, 590, 225
Ciotti L., Ostriker J. P., 2001, ApJ, 551, 131
David L. P., Jones C., Forman W., Daines S., 1994, MNRAS, 428, 544
Dokuchaev V. P., 1964, Sov. Astron., 8, 23
El-Zant A. A., Hoffman Y., Primack J. P., Combes F., Shlosman I., 2004, ApJ, 607, L75
Fabian A. C., 1994, ARAA, 32, 277
Fabian A. C., Sanders J. S., Ettori S., Tayler G. B., Allen S. W., Crawford C. W., Iwasawa K., Johnstone R. M., 2001, MNRAS, 321, L33
Fabian A. C., Voigt L. M., Morris R. G., 2002, MNRAS, 335, L71
Gerhard O., Kronawitter A., Saglia R. P., Bender R., 2001, AJ, 121, 1936
Ghigna S., Moore B., Governato F., Lake G., Quinn T., Stadel J., 2000, ApJ, 544, 616
Just A., Deiss B. M., Kegel W. H., Bohringer H., Morgil G. E., 1990, ApJ, 400, 353
Kaastra J. S. et al., 2004, A&A, 413, 415
Kaiser C. R., Binney J., 2003, MNRAS, 338, 837
Kim W.-T., Narayan R., 2003a, ApJ, 596, 889
Kim W.-T., Narayan R., 2003b, ApJ, 596, L139
Miller L., 1986, MNRAS, 220, 713
Narayan R., Medvedev M. V., 2001, ApJ, 562, L129
Natarayan P., Kneib J.-P., Smail I., 2002, ApJ, 580, L11
Navarro J. F., Frenk C. S., White S. D. M., 1997, ApJ, 490, 493
Ostriker E., 1999, ApJ, 513, 252
Peres C. B., Fabian A. C., Edge A. C., Allen S. W., Johnstone R. M., White D. A., 1998, MNRAS, 298, 416
Peterson J. R. et al., 2001, A&A, 365, L104
Peterson J. R., Kahn S. M., Paerels F. B. S., Kaastra J. S., Tamura T., Bleeker J. A. M., Ferrigno C., Jernigan J. G., 2003, ApJ, 590, 207
Raphaeli Y., Salpeter E. E., 1980, ApJ, 240, 20
Ruderman M. A., Spiegel E. A., 1971, ApJ, 151, 679
Ruszkowski M., Begelman M. C., 2002, ApJ, 581, 223
Salucci P., Ashman K. M., Persic M., 1991, ApJ, 379, 89
Sanchez-Salcedo F. J., Brandenburg A., 1999, ApJ, 522, L35
Sanchez-Salcedo F. J., Brandenburg A., 2001, MNRAS, 322, 67
Takamiya T., Sofue Y., 2000, ApJ, 534, 670
Trujillo I., Burkert A., Bell E. F., 2004, ApJ, 600, L39
Tucker W. H., Rosner R., 1983, ApJ, 267, 547
Voigt L., Fabian A., 2004, MNRAS, 347, 1130
Voigt L. M., Schmidt R. W., Fabian A. C., Allen S. W., Johnstone R. M., 2002, MNRAS, 335, L7
Zakamska N. L., Narayan R., 2003, ApJ, 582, 162

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